PSI Center for Accelerator Science and Engineering

RADSUM 2025

Efficient Magnet Designs and Radiation effects for PSI

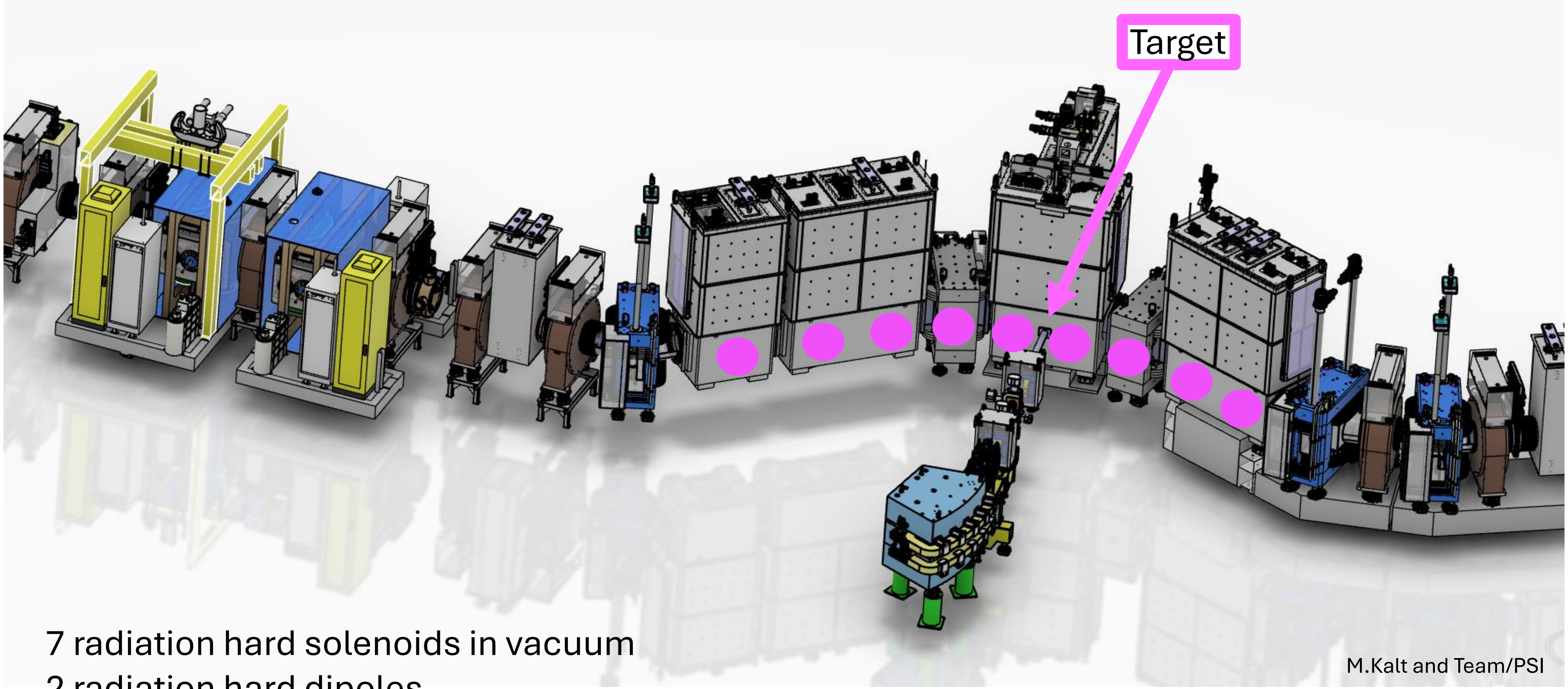
Ciro Calzolaio, Michal Duda, Roman Farruggia, Garcia Rodrigues Henrique, Stephane Sanfilippo

RADSUM, 17 January 2025

Contents

- The HIPA Accelerator and the radiation hard magnets at PSI.
- Possible candidate resistive magnets to be replaced by superconducting ones.
- Superconducting magnets for the HIPA accelerator
  - The Pilot Nb-Ti solenoid.
  - Preliminary measurements at PSI.
  - The HTS demonstrator.
- Conclusions

New Target Region



M.Kalt and Team/PSI

7 radiation hard solenoids in vacuum
2 radiation hard dipoles

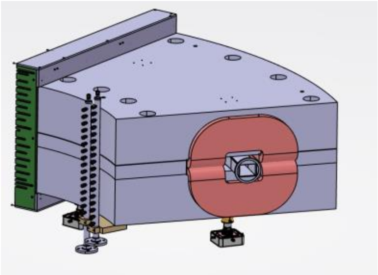
● radiation hard magnets

Long term goal: replace resistive magnets in HIPA

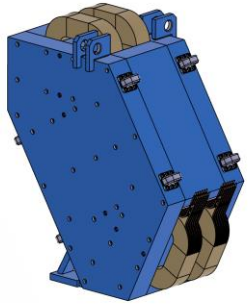
~280 copper coil resistive magnets

~70 magnets with Mineral Insulated Cables (MIC) (highly radiative environment)

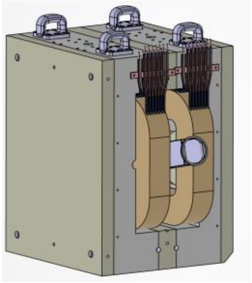
Transport Solenoid
65 kW
0.55 T
(1 T if superconducting)



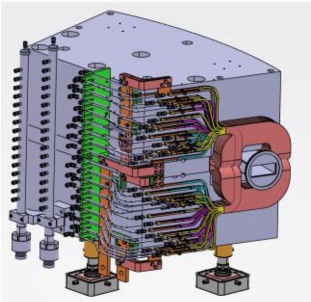
AHC
128 kW
1.564 T



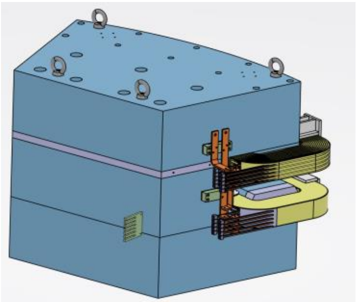
AHO
145 kW
1.5 T



AHM, AHN
67 kW
1.5 T



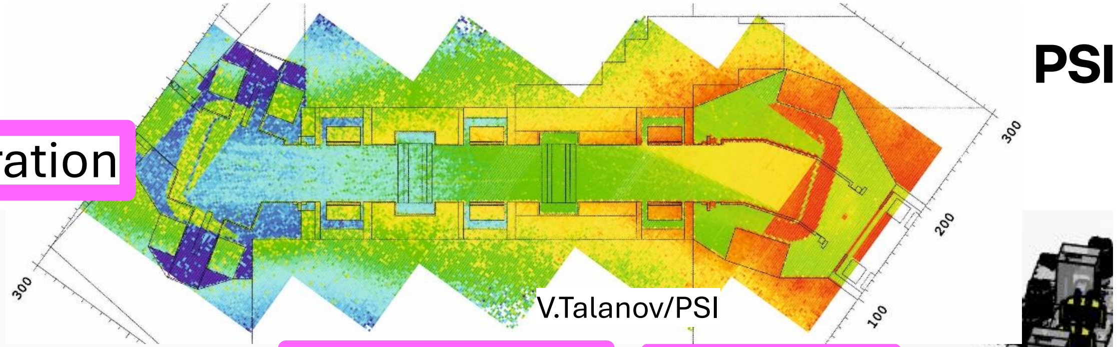
AHB
189 kW
1.8 T



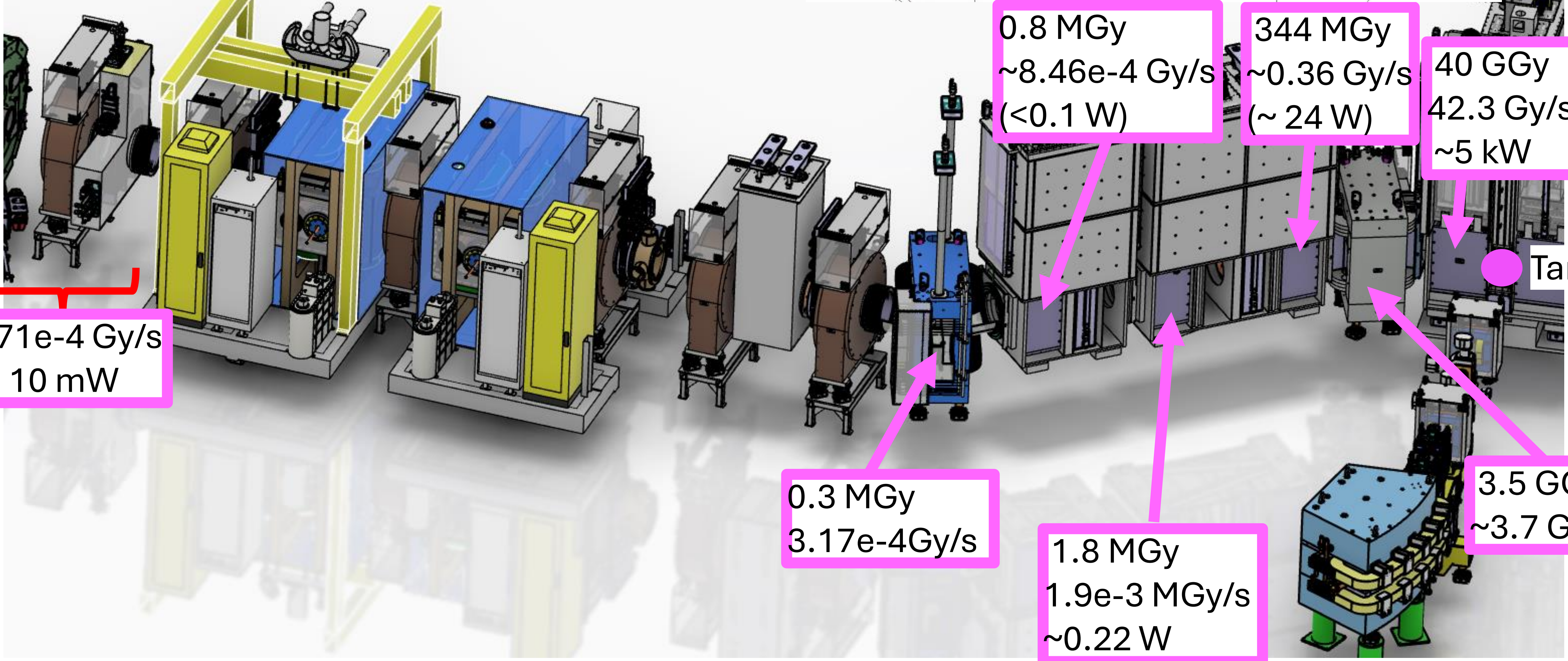
AHD1, AHD2
74 kW
1.2 T

Radiation load along beamline MuH2

Absorbed dose over 30 years of operation



V.Talanov/PSI



1.71e-4 Gy/s
10 mW

0.3 MGy
3.17e-4Gy/s

0.8 MGy
~8.46e-4 Gy/s
(<0.1 W)

1.8 MGy
1.9e-3 MGy/s
~0.22 W

344 MGy
~0.36 Gy/s
(~ 24 W)

40 GGy
42.3 Gy/s
~5 kW

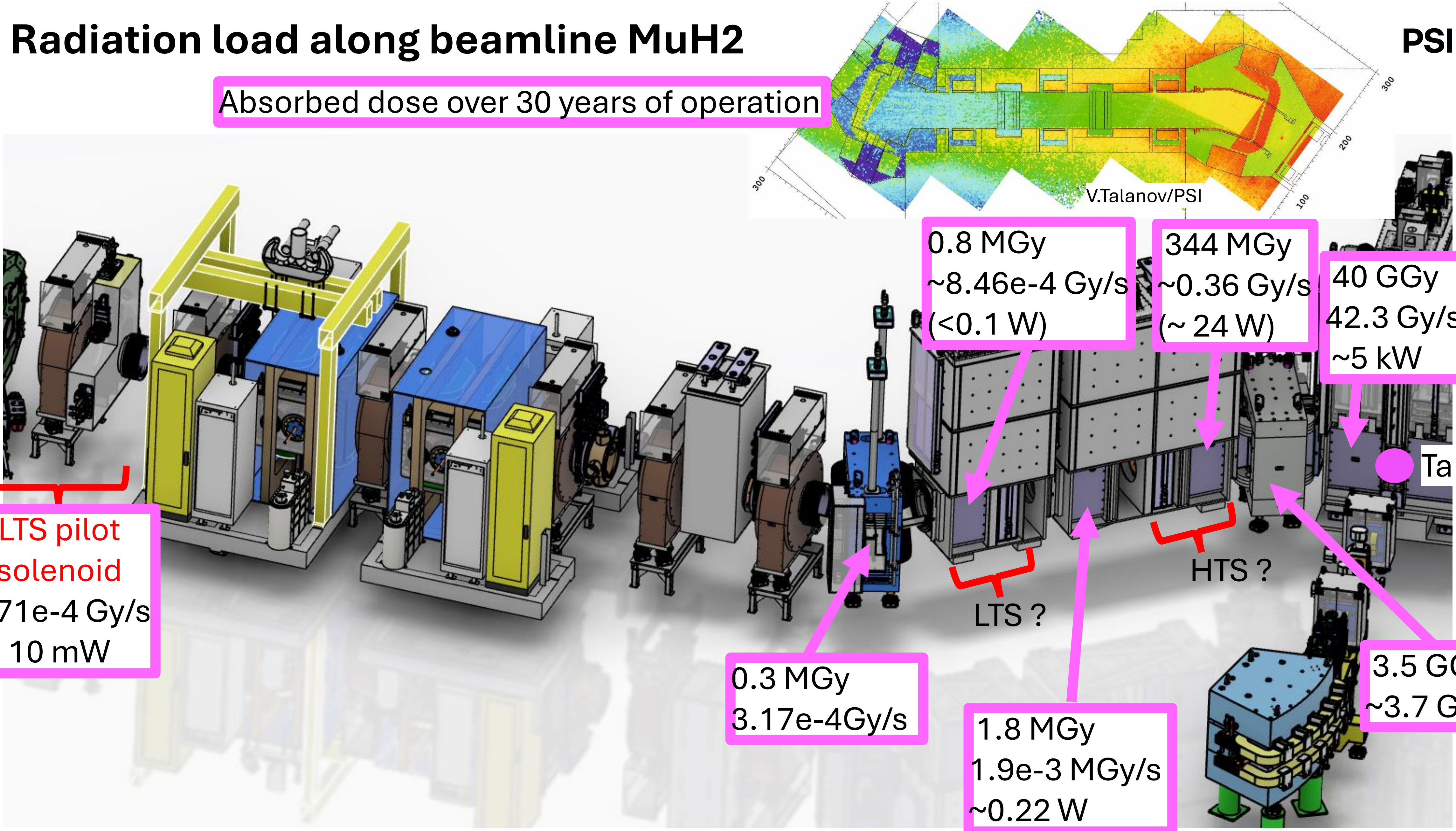
3.5 GGy
~3.7 Gy/s

Target

Radiation load along beamline MuH2

PSI

Absorbed dose over 30 years of operation



V.Talanov/PSI

LTS pilot solenoid
1.71e-4 Gy/s
10 mW

0.3 MGy
3.17e-4Gy/s

0.8 MGy
~8.46e-4 Gy/s
(<0.1 W)

LTS ?

1.8 MGy
1.9e-3 MGy/s
~0.22 W

344 MGy
~0.36 Gy/s
(~ 24 W)

HTS ?

40 GGy
42.3 Gy/s
~5 kW

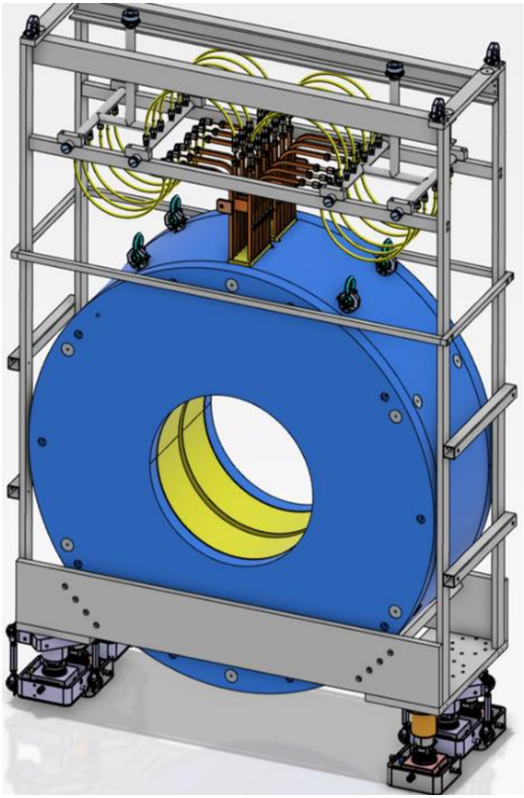
Target

3.5 GGy
~3.7 Gy/s

Transport solenoid:
resistive vs superconducting at a glance

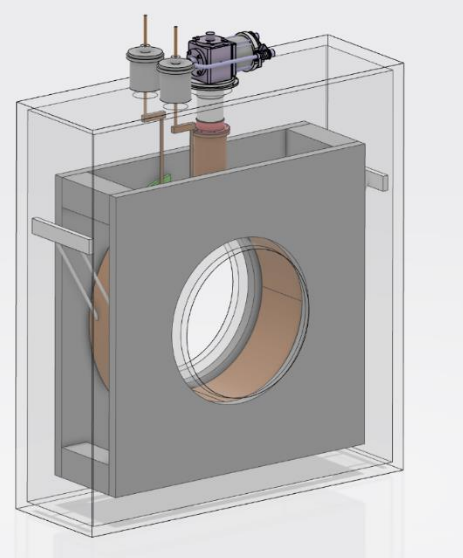
Resistive magnet

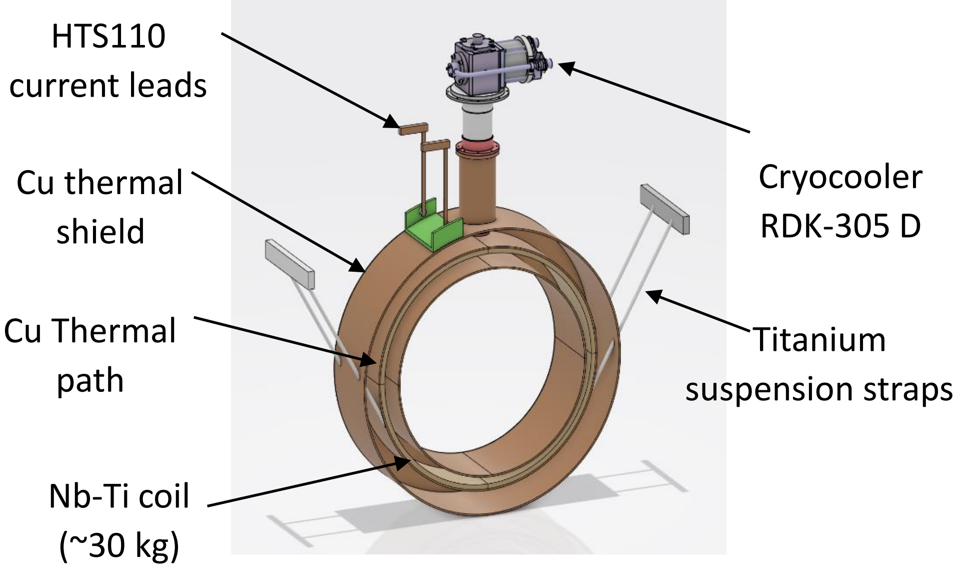
- Cu coils mass: 1300 kg
- J_e=5 A/mm^2
- Peak field: 0.55 T
- Peak power consumption: 65 kW
- Average power consumption: ~20 kW



Superconducting magnet

- Cold mass (coil + yoke): ~ 110 kg
- J_e=150 A/mm^2
- Peak field: ≥1.0 T
- Peak power consumption: 8.6 kW
- Average power consumption: 7.6 kW
  - 6.6 kW from cryocoolers → it could drop to 3.6 kW at lower radiation environments
  - 0.5 kW from the turbopump
  - 0.5 kW from losses in the cable + Cu leads



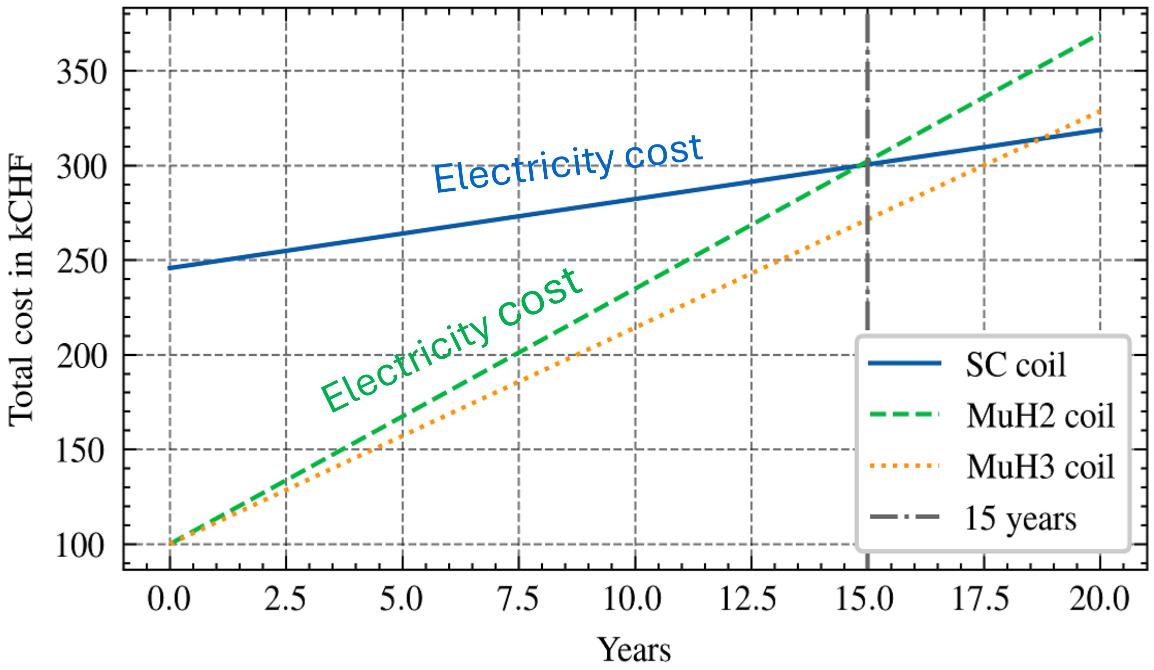


Pilot Solenoid for IMPACT

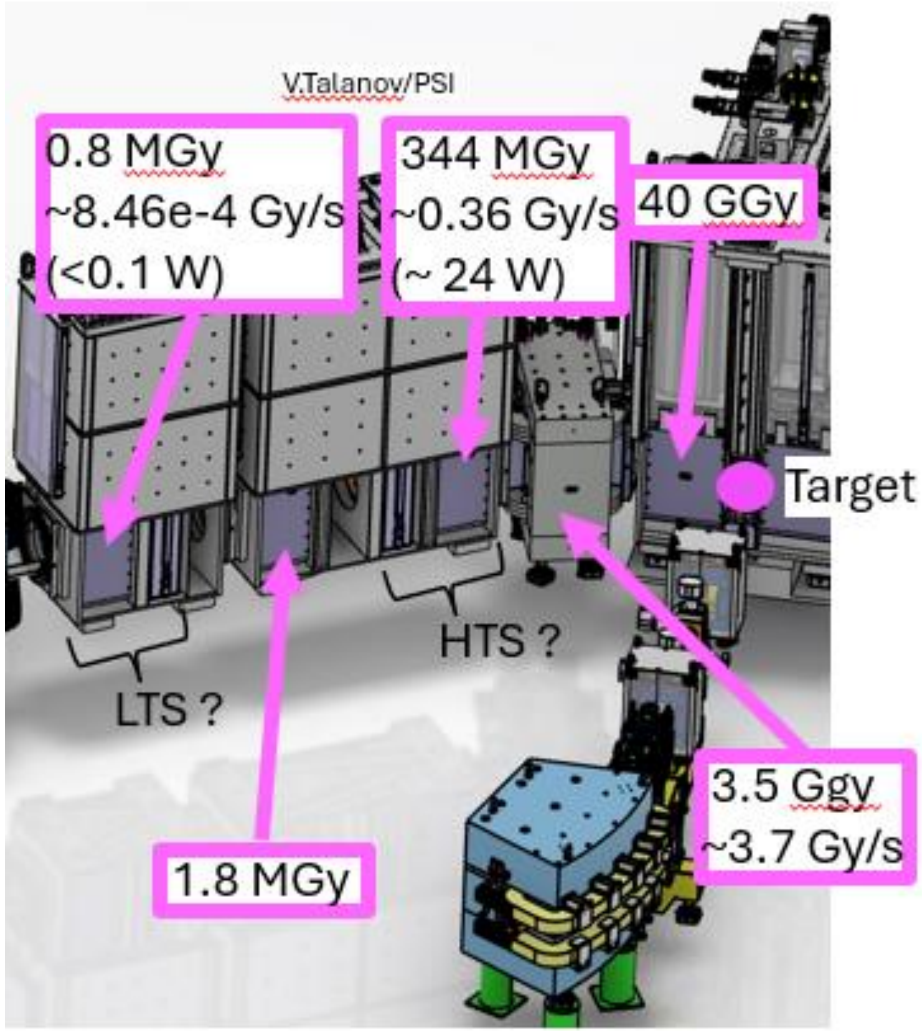
	Resistive	Superconducting
Average Power [kW]	20	7.6
Working hours/year	4000	4000
n. years	20	20
Tot. energy [MWh]	1600	608
Energy saving [MWh]	0	992
Energy price [CHF/MWh]	200	200
Tot. electricity price [kCHF]	320	121.6
Runnig cost saving [kCHF]	0	198.4
Yearly carbon Intensity [gCO2eq/kWh]	40	40
CO2 equivalent [tons]	64	24.32
CO2 equivalent saving [tons]	0	39.68
Capital cost [kCHF]	225	350
Price break even [years]		12.60

Solenoid main parameters

Solenoid parameters	Cu	SC
Inner Diameter [mm]	550	600
Total Length [mm]	465	465
Peak field [T]	0.55	1
Field integral [Tm]	0.3	0.3
Working hours / year	4000	4000
Duration of operation	>20 years	>20 years

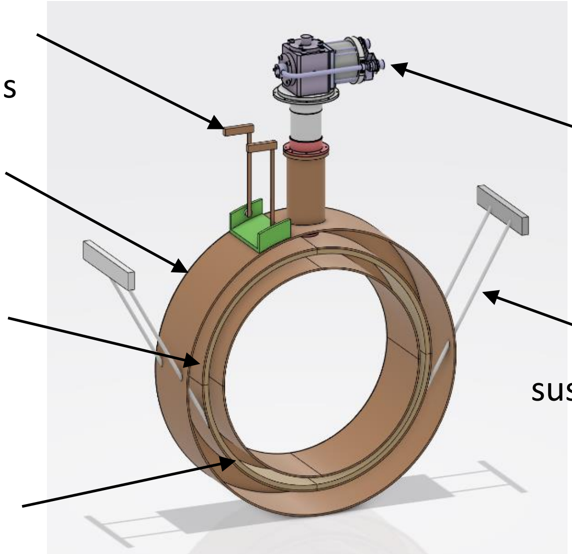


Pilot Solenoid for IMPACT



Heat budget	**P [W]**		
1st stage (T~60 K)			
100 A Current leads	9.33		
Structural Support	1.2		
Thermal Radiation	1.6		
Sensor wires	0.3		
neutron dose	?		
Tot.	12.43		
2nd stage		**2nd stage**	
2nd solenoid	P [W]	**3rd solenoid**	P [W]
HTS leads	0.04	HTS leads	0.04
Structural support	0.12	Structural support	0.12
Thermal radiation	0.13	Thermal radiation	0.13
Sensor wires	0.15	Sensor wires	0.15
neutron dose	**0.150**	**neutron dose**	**0.012**
Tot.	0.590	Tot.	0.452

Pilot Solenoid for IMPACT



HTS110
current leads

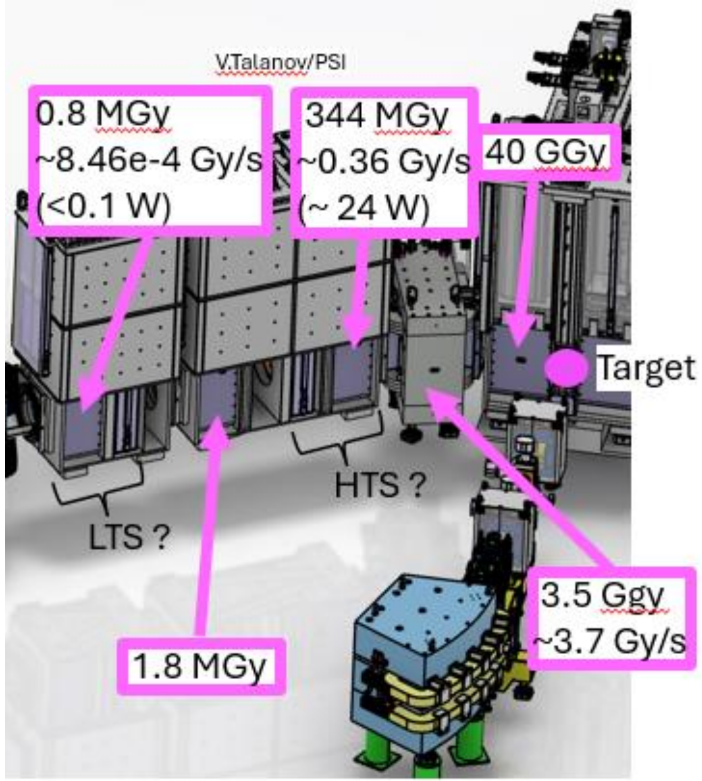
Cu thermal
shield

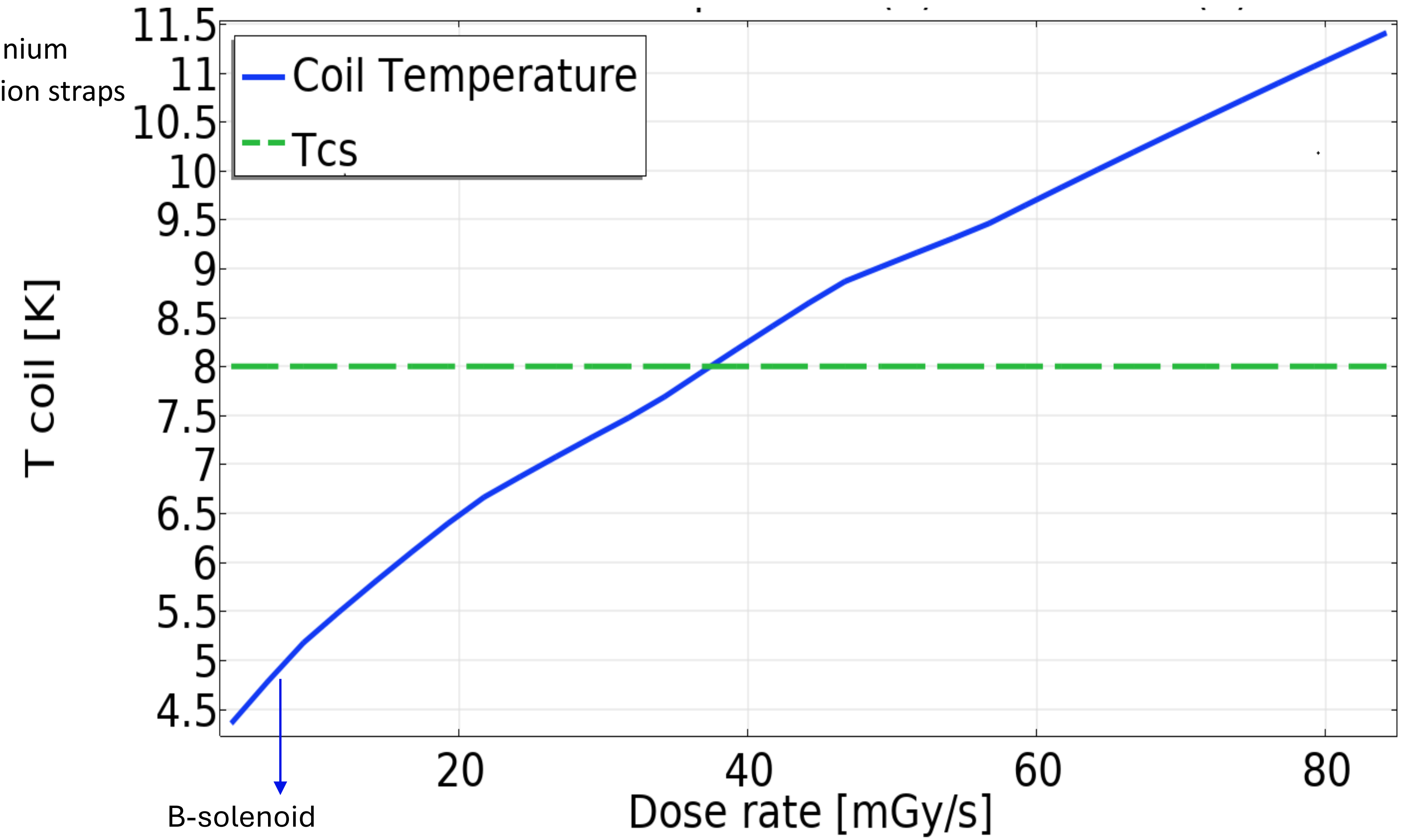
Cu Thermal
path

Nb-Ti coil
(~30 kg)

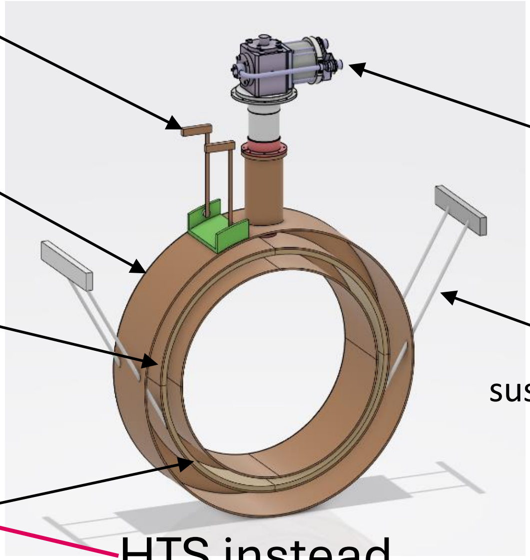
Cryocooler
RDK-305 D

Titanium
suspension straps





HTS demonstrator



HTS110 current leads

Cryocooler RDK-305 D

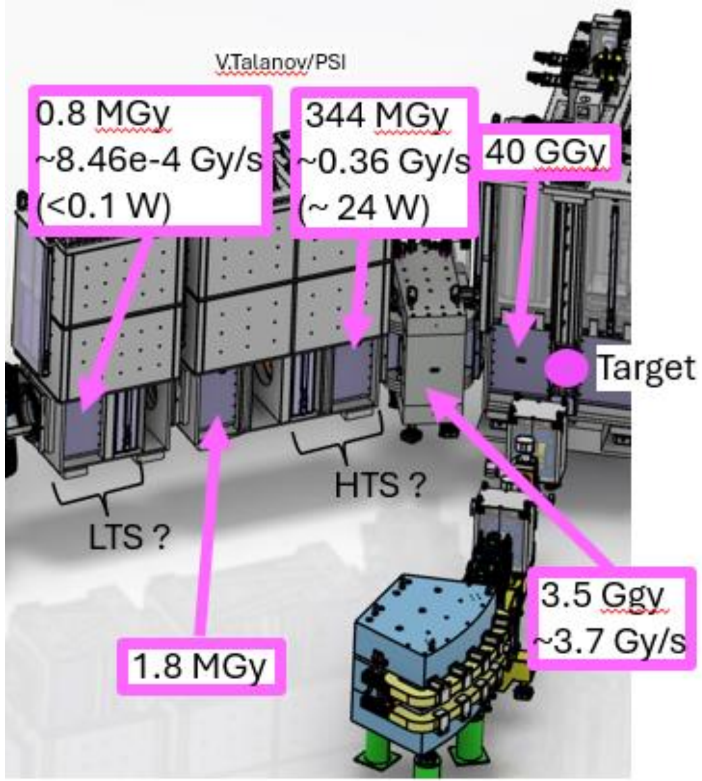
Cu thermal shield

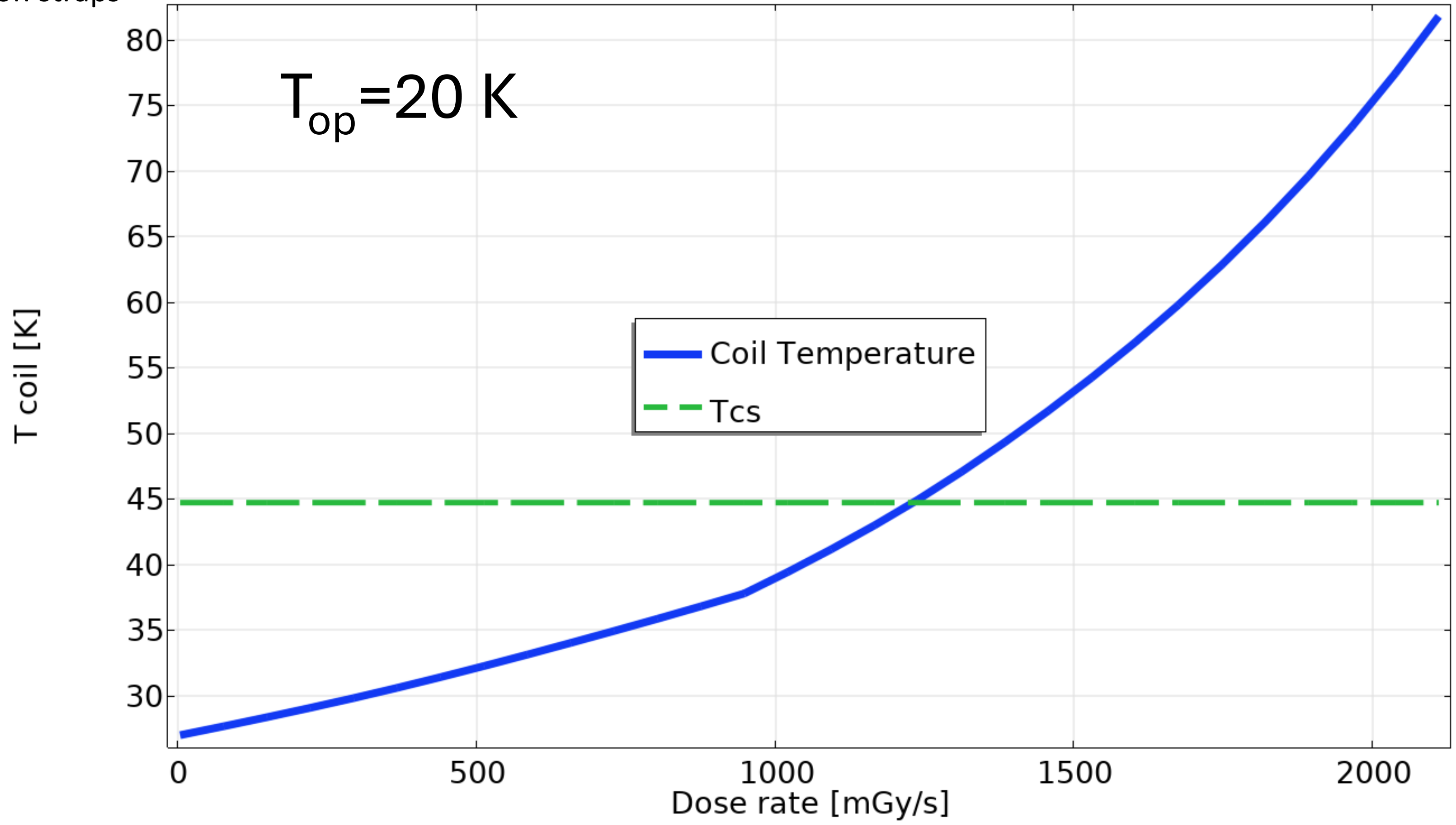
Titanium suspension straps

Cu Thermal path

~~Nb-Ti coil (~30 kg)~~

HTS instead





Demonstrator Magnet for high radiation environment

Main Goal: Gain experience regarding the operation of superconducting magnets in a high radiation environment

1. Design and build a superconducting magnet
2. Place it inside a high radiation environment (i.e. accelerator enclosure)
3. Measure the operational properties of the magnet during operation (I_c & T_c)
4. Measure the radiation level during operation
5. → Combine this information and draw conclusions regarding the life cycle of a SC magnet in a high radiation environment

→ Collaboration with Polytech Turin for radiation assessment

HTS superconducting magnets

Advantages

- Increased performance
- Thermal stability (wrt LTS)

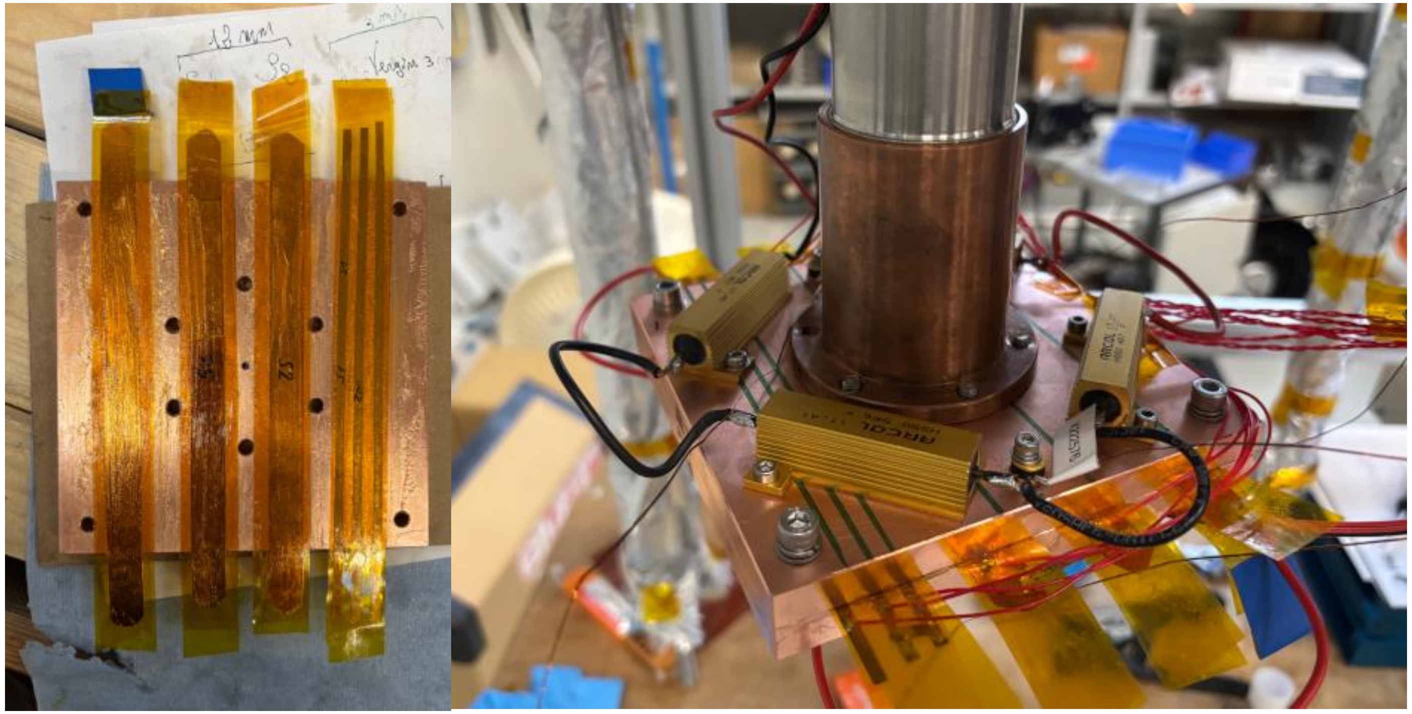
  Large temperature margin (including beam deposited energy)
- Compact design
- Saving electric consumption
- Reduced cost for power supply
- T_{op}~20-30 K

Drawbacks

- Higher capital cost
- Cryogenics
- Quench detection system
- AC losses in time varying field
- Radiation damages

- *Limits for superconductor degradation?*
- *No organic insulation*
  - *non insulated coils or*
  - *steel insulated coils*

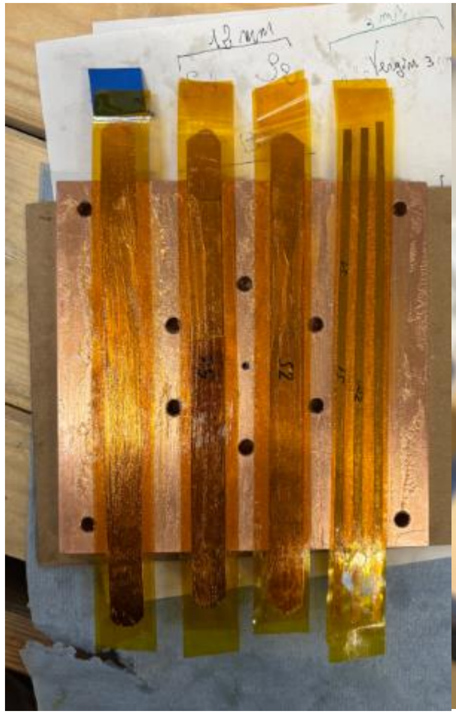
Sample irradiated at room temperature at PSI

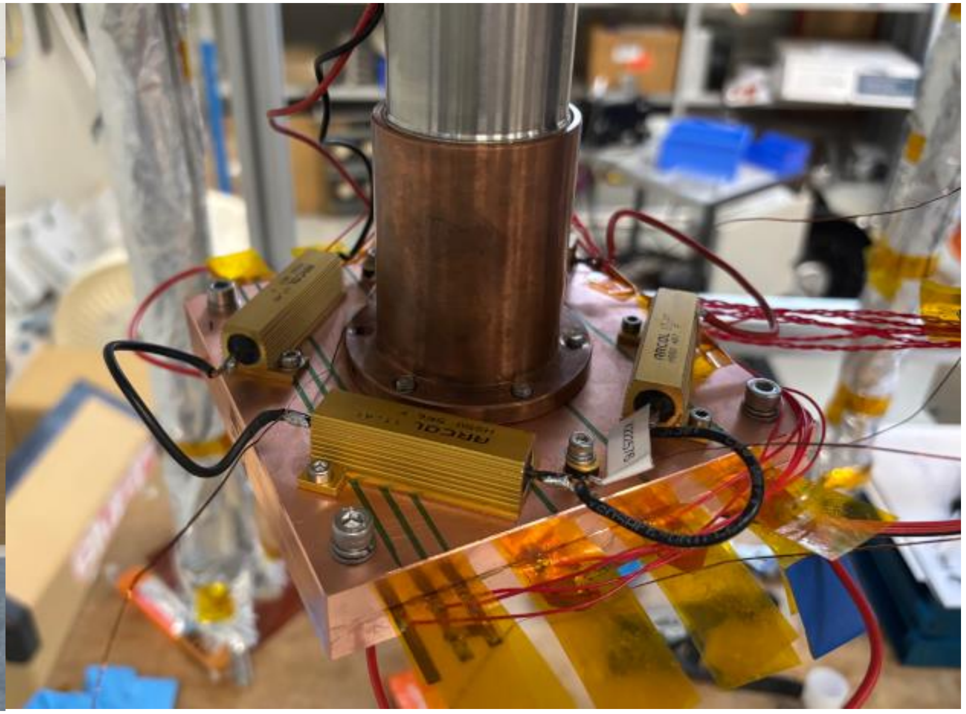


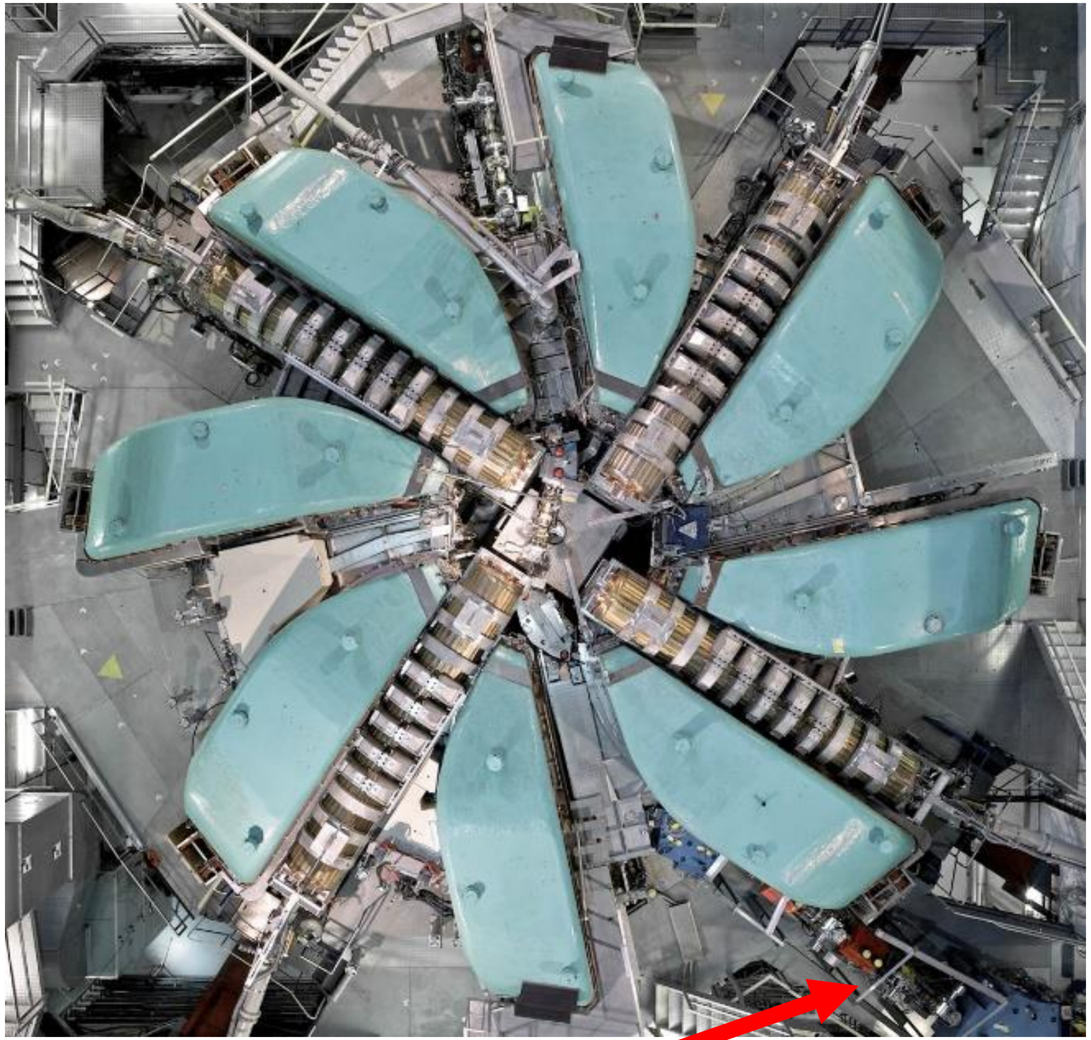
Test station for conduction cooled magnets

- Ciro Calzolaio (PSI)
- Michal Duda (PSI)
- Garcia Rodrigues Henrique (PSI)
- Martina Casciello (Politecnico di Torino)

Sample irradiated at room temperature at PSI



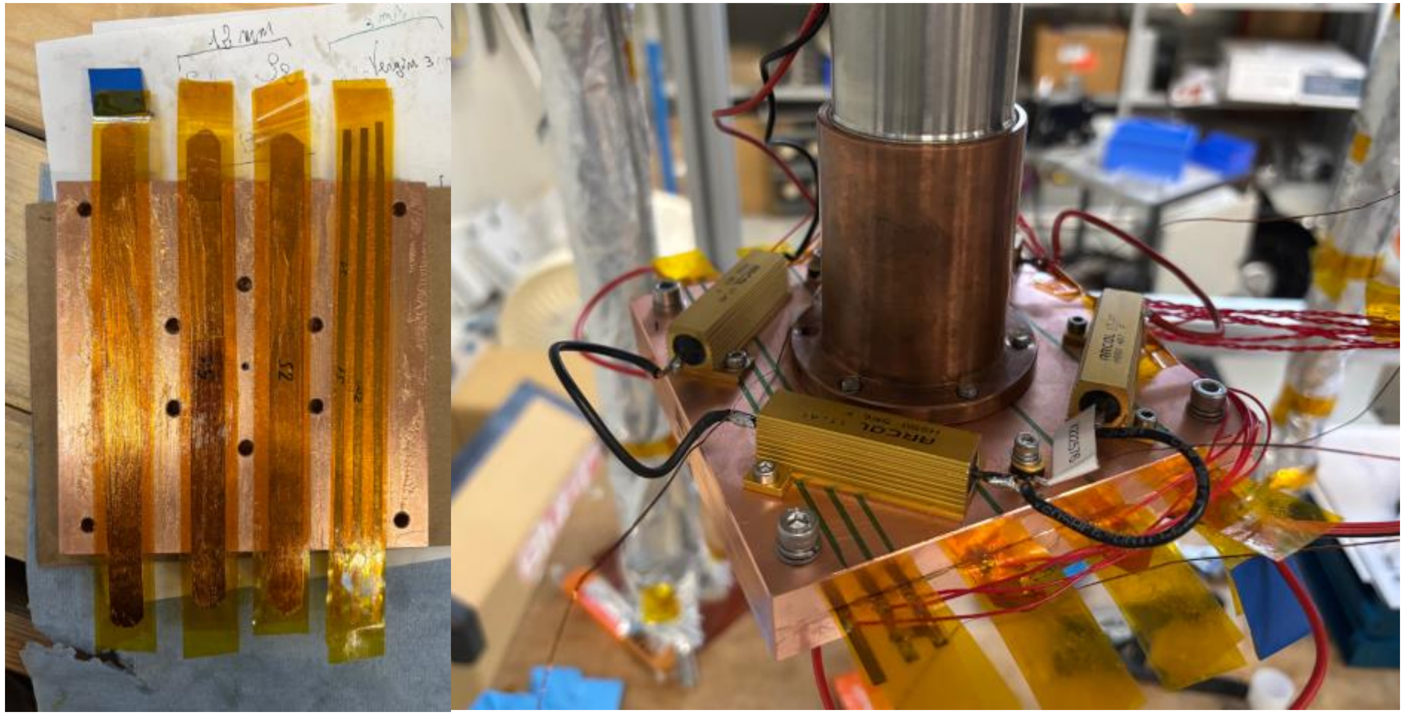


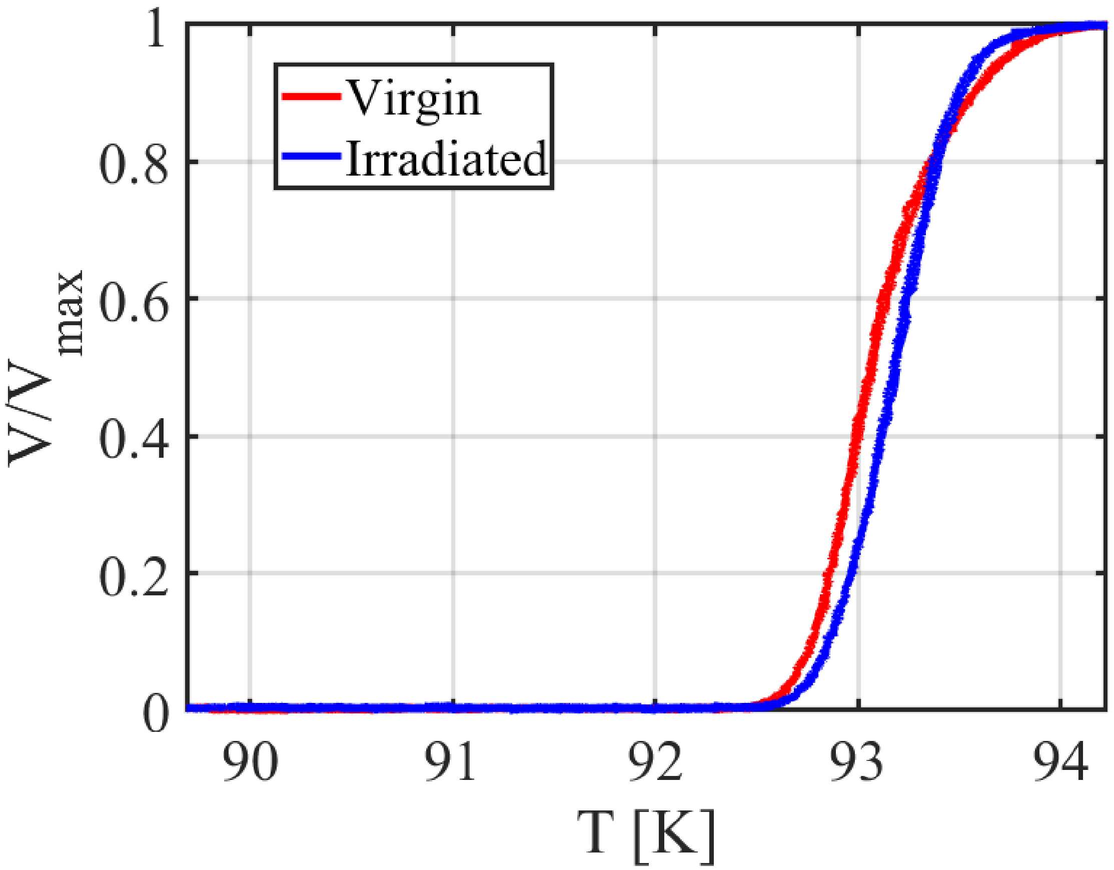


Sample location

- Ciro Calzolaio (PSI)
- Michal Duda (PSI)
- Garcia Rodrigues Henrique (PSI)
- Martina Casciello (Politecnico di Torino)

Sample irradiated at room temperature at PSI





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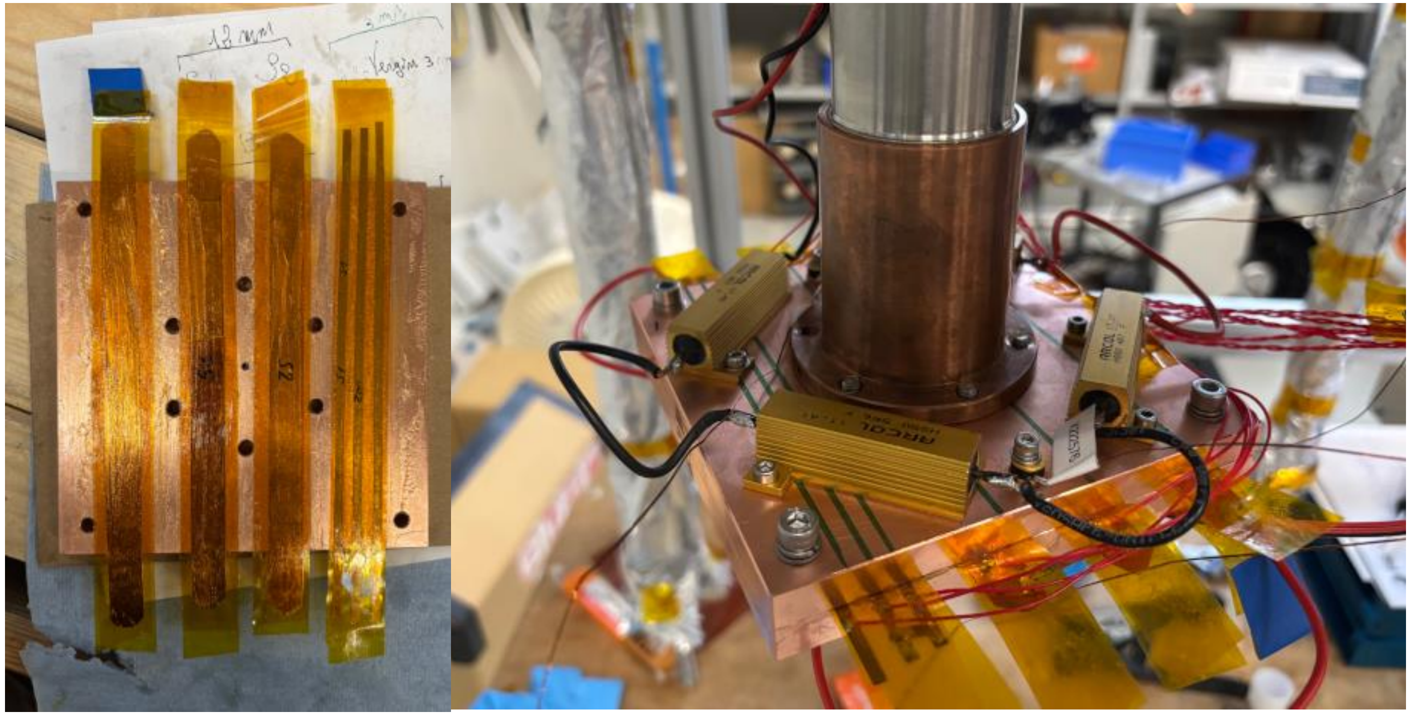
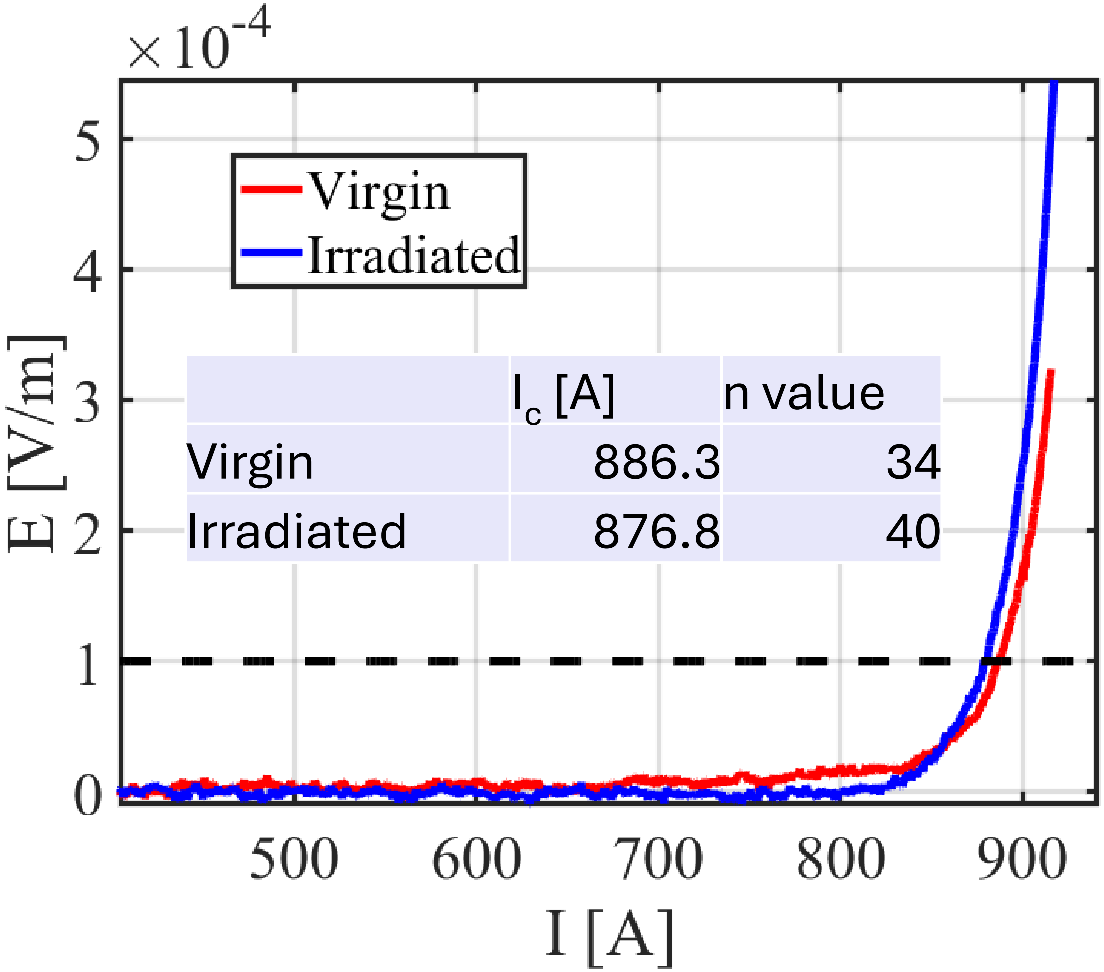
Sample irradiated at room temperature at PSI

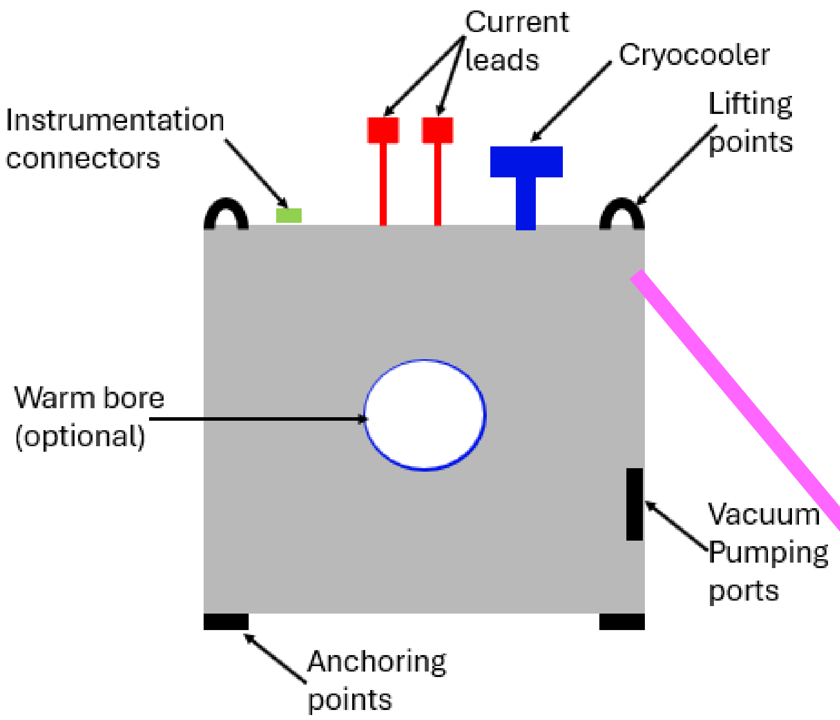




	I_c [A]	n value
Virgin	886.3	34
Irradiated	876.8	40

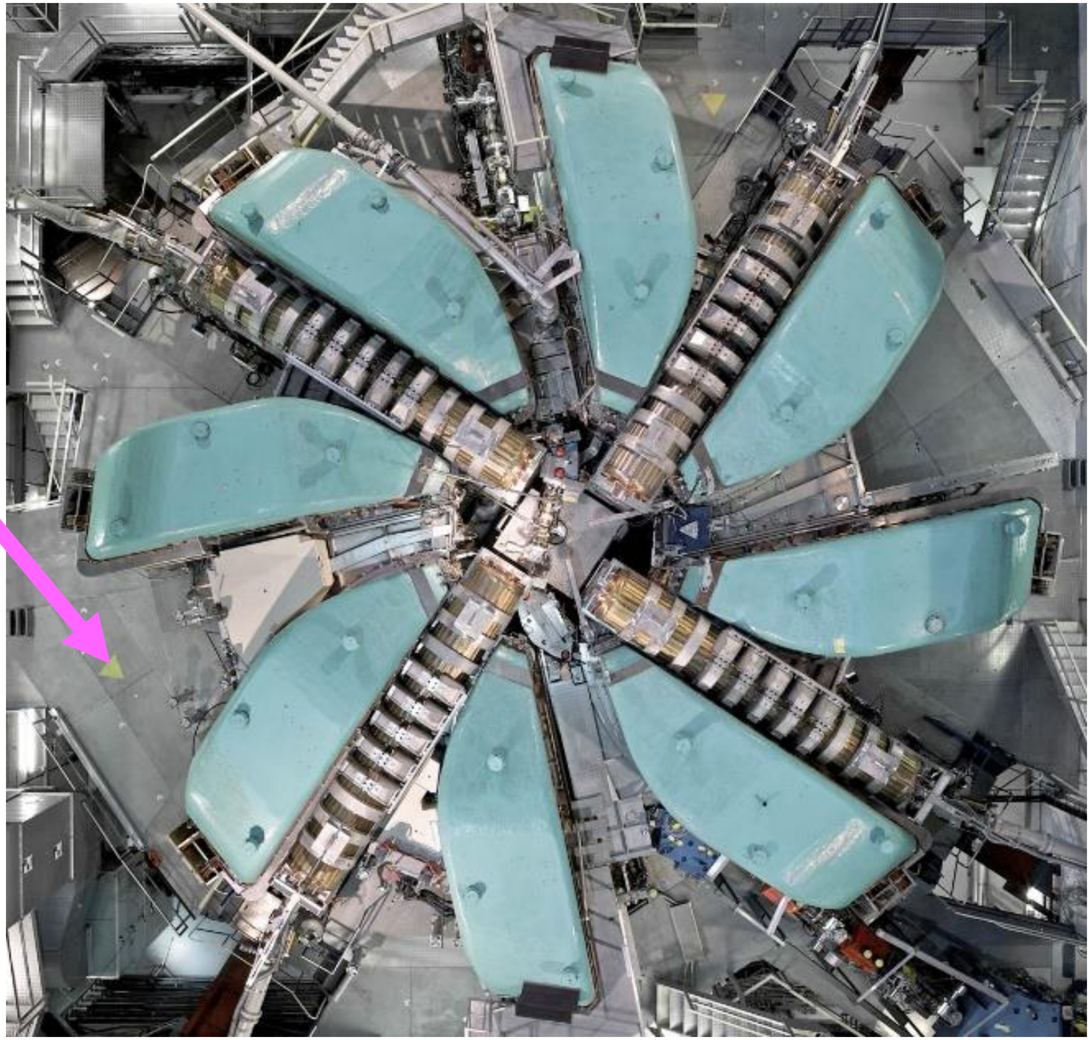
- Ciro Calzolaio (PSI)
- Michal Duda (PSI)
- Garcia Rodrigues Henrique (PSI)
- Martina Casciello (Politecnico di Torino)

HTS Demonstrator



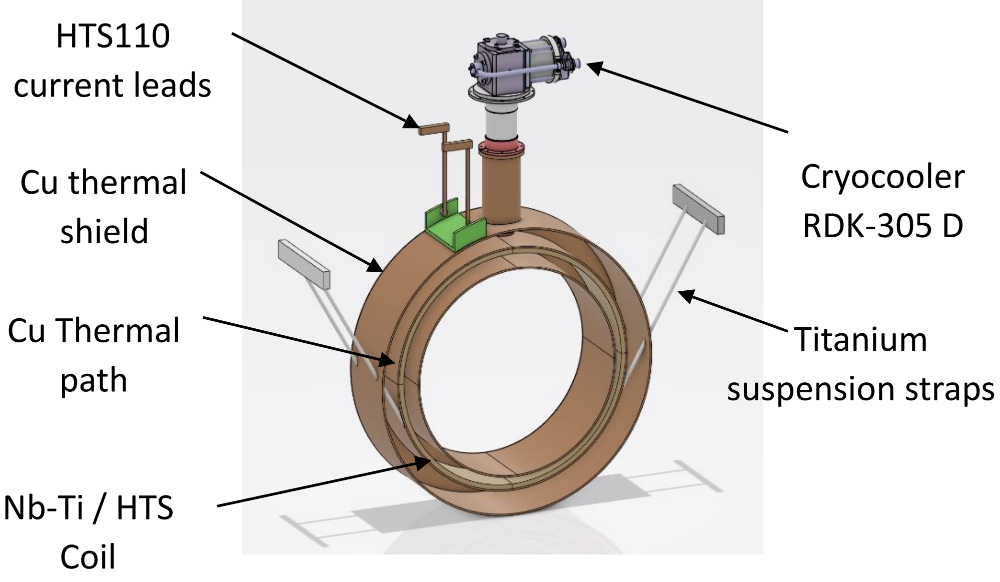
Dose rate: ~3e-4 Gy/s

Neutron spectrum measured but we are still waiting for the results…



Goal: build a test magnet, place it inside the cyclotron bunker and irradiate it for one operational period (4000 hrs) in 2026

Superconducting magnets for HIMB



HTS110 current leads

Cu thermal shield

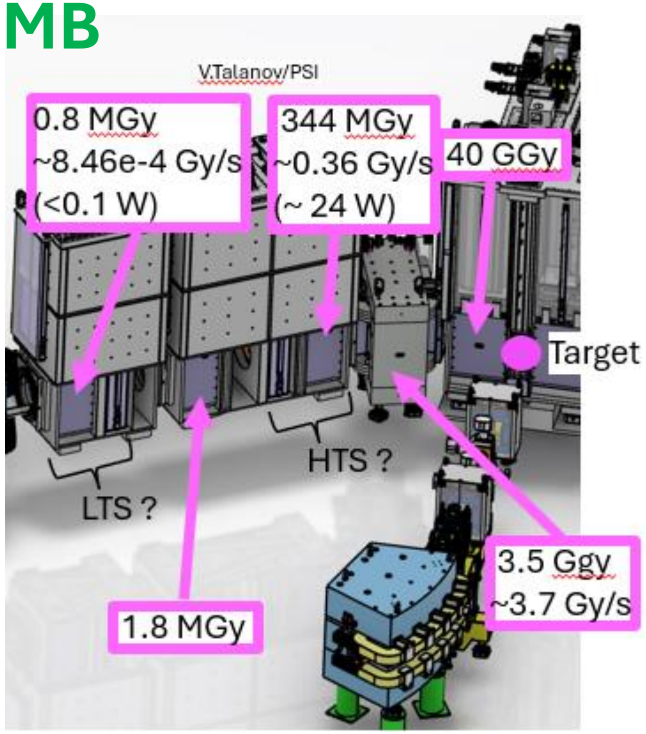
Cu Thermal path

Nb-Ti / HTS Coil

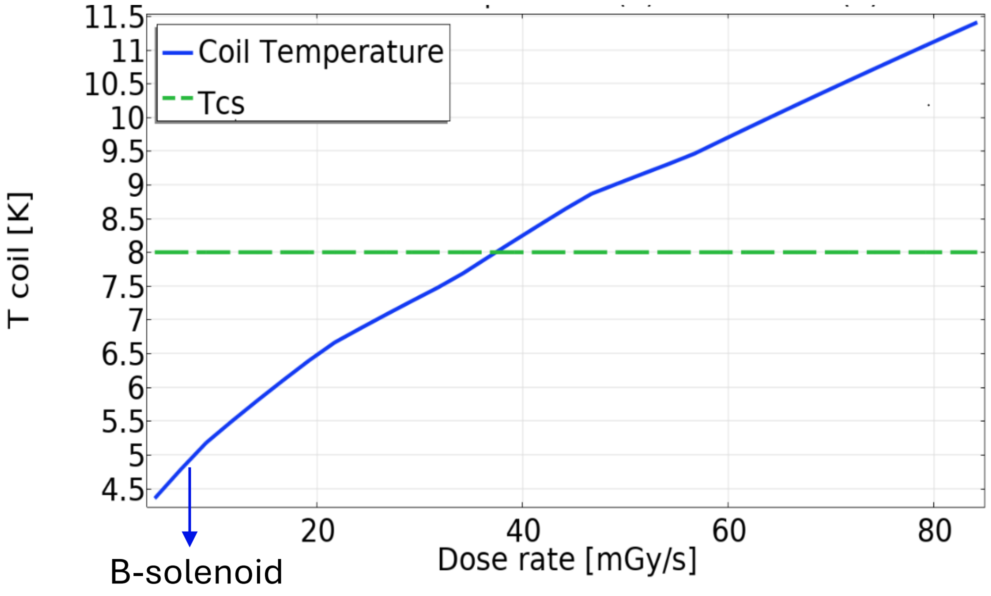
Cryocooler RDK-305 D

Titanium suspension straps

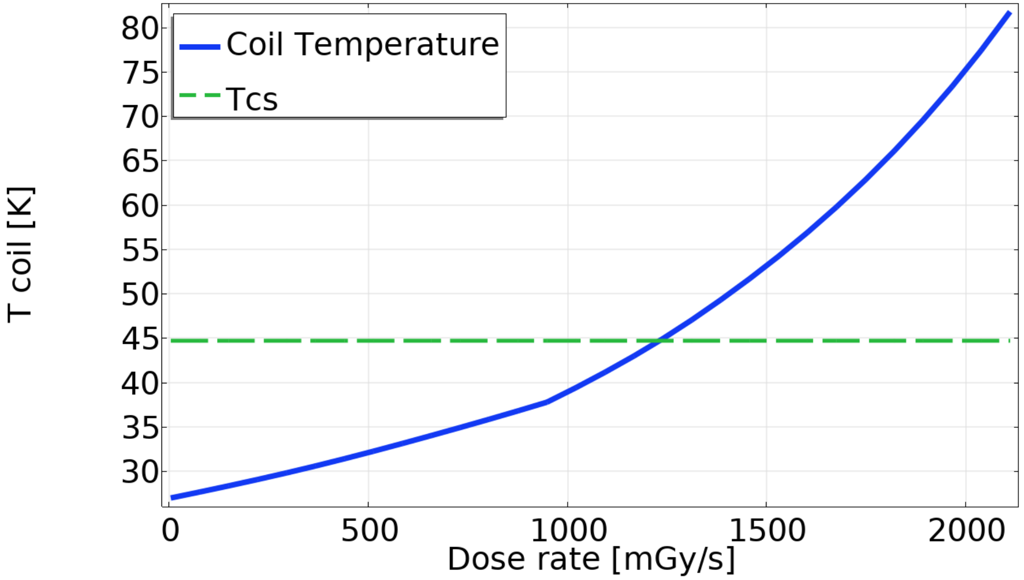
- Non insulated;
- Metal insulated;
- …



LTS (Nb-Ti) coil



HTS coil



Conclusion

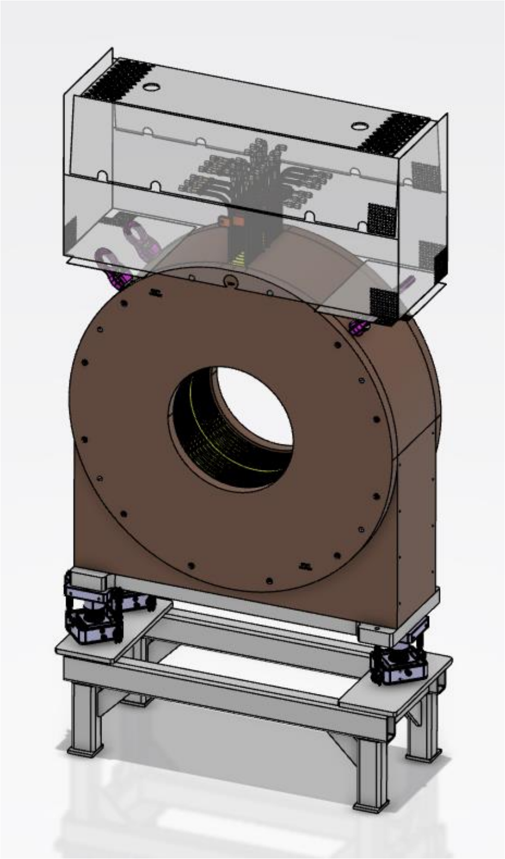
- The total power consumption of the HIMB magnets is 3.1 MW (20% more than current magnets).
- Superconducting magnets could both save energy and improve machine performance.
- We plan to build
  - a Nb-Ti pilot solenoid for low-radiation regions and
  - A ReBCO demonstrator to explore the HTS technology for higher radiation environments.
- The SMILE (Superconducting Magnets to Improve Large research facilities Efficiency) initiative was launched to address these topics.

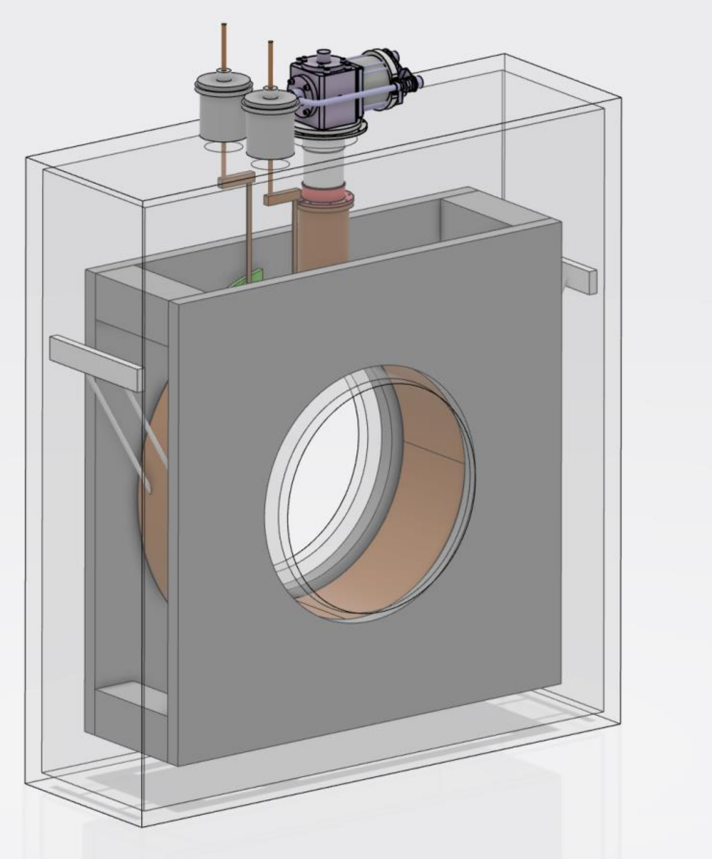
- **The goal is to adopt superconducting materials in PSI's accelerator-driven research infrastructures to**
  - **lower the power consumption and**
  - **to increase the performance.**

Thank you

Thank you

LTS Solution: Pilot





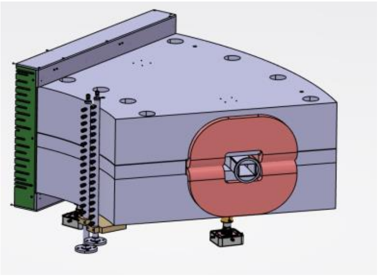
Max. field 0.55 T
Power at max. field 65 kW

Max. field 1 T
Power at max. field ?? kW

Long term goal: replace resistive magnets in HIPA

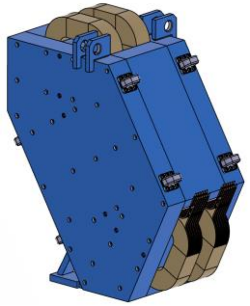
~280 copper coil resistive magnets

~70 magnets with Mineral Insulated Cables (MIC) (highly radiative environment)



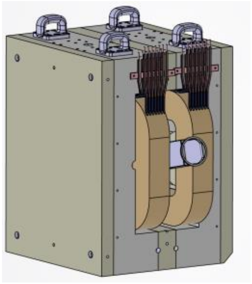
AHC

Power	128 kW
Field	1.564 T
Integral	2.8 Tm
Size	2x1.5x0.8 m
Weight	12.5 t



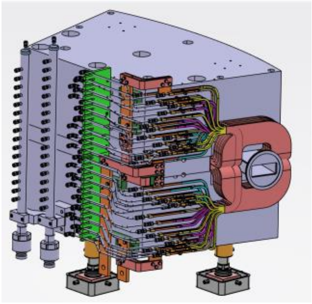
AHO

Power	145 kW
Field	1.5 T
Integral	4.5 Tm
Size	2.9x2.6x1.5 m
Weight	51 t



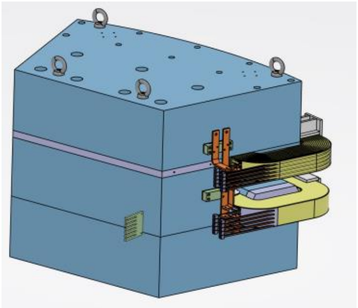
AHM, AHN

Power	67 kW
Field	1.5 T
Integral	3.75 Tm
Size	2x1.5x1.2 m
Weight	22 t



AHB

Power	189 kW
Field	1.8 T
Integral	2.9 Tm
Size	1x0.7x0.7 m
Weight	4.2 t

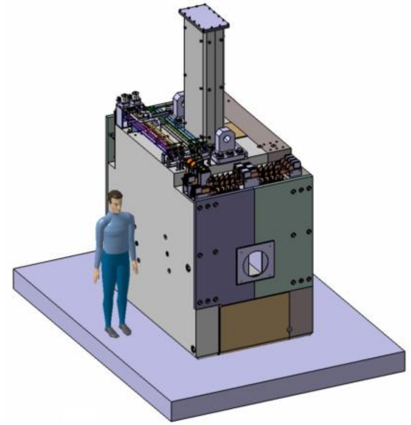


AHD1, AHD2

Power	32 / 74 kW
Field	1.2 / 1.15 T
Integral	2.2 / 2.3 Tm
Size	2x1.2x1.5 m
Weight	19 t

AHL

Power	61 kW
Field	1.12 T
Integral	2.5 Tm
Size	2.3x2.3x1.5 m
Weight	48 t

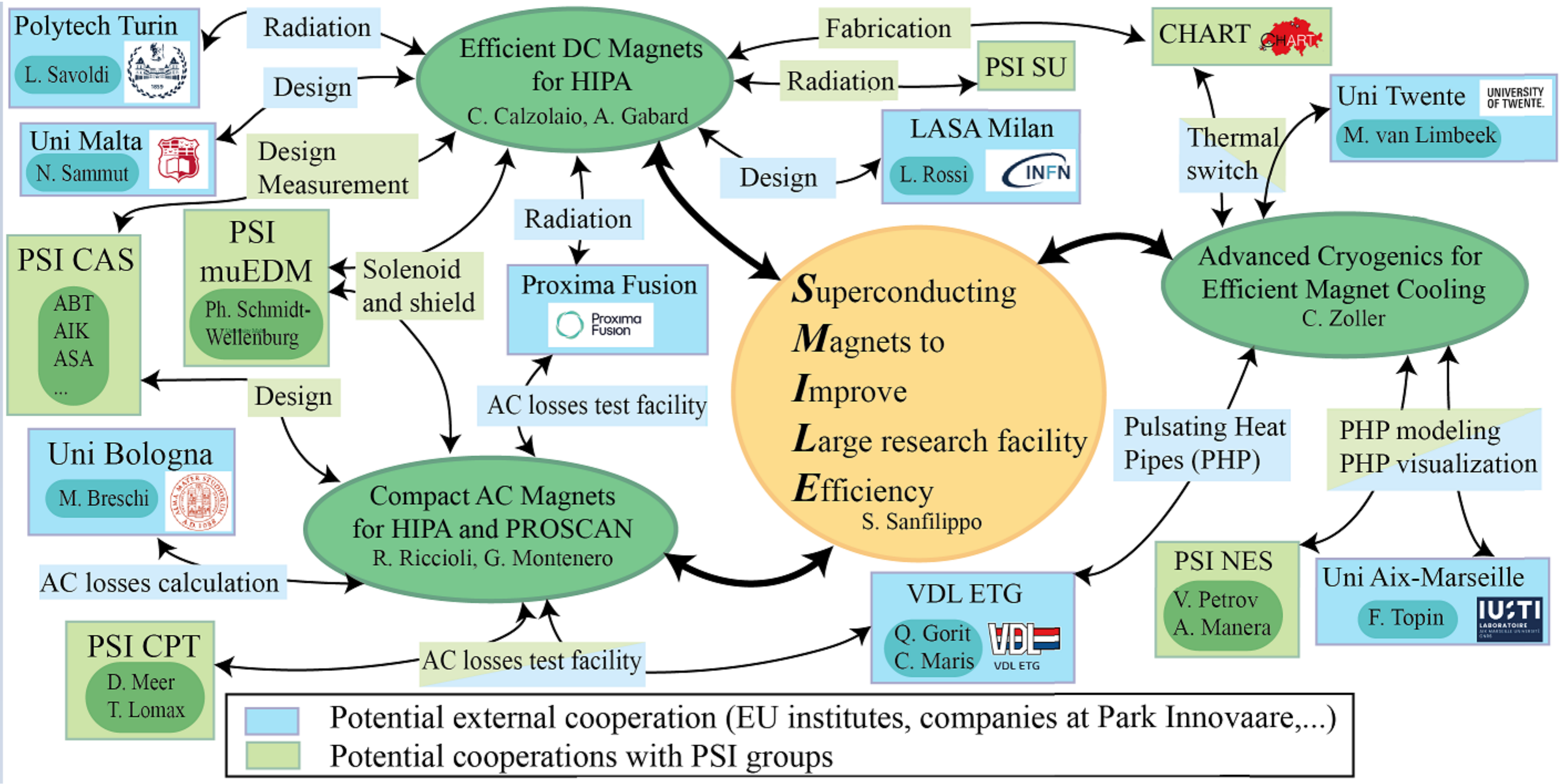


Power only, full slide in annex

Radiation hard (MIC coils)

SMILE: mid-term initiative (min. 4 years)

Goals: Sustainable energy management for the infrastructure of PSI,
with more efficient and improved performance of magnets



Polytech Turin
L. Savoldi

Radiation

Design

Uni Malta
N. Sammut

Design
Measurement

Efficient DC Magnets
for HIPA
C. Calzolaio, A. Gabard

Fabrication

Radiation

CHART

PSI SU

LASA Milan
L. Rossi

Design

Thermal
switch

Uni Twente
M. van Limbeek

PSI CAS
ABT
AIK
ASA
...

PSI
muEDM
Ph. Schmidt-Wellenburg

Solenoid
and shield

Radiation

Proxima Fusion

AC losses test facility

Design

Superconducting
Magnets to
Improve
Large research facility
Efficiency
S. Sanfilippo

Advanced Cryogenics for
Efficient Magnet Cooling
C. Zoller

Pulsating Heat
Pipes (PHP)

PHP modeling
PHP visualization

Uni Bologna
M. Breschi

Compact AC Magnets
for HIPA and PROSCAN
R. Riccioli, G. Montenero

AC losses calculation

PSI NES
V. Petrov
A. Manera

Uni Aix-Marseille
F. Topin

VDL ETG
Q. Gorit
C. Maris

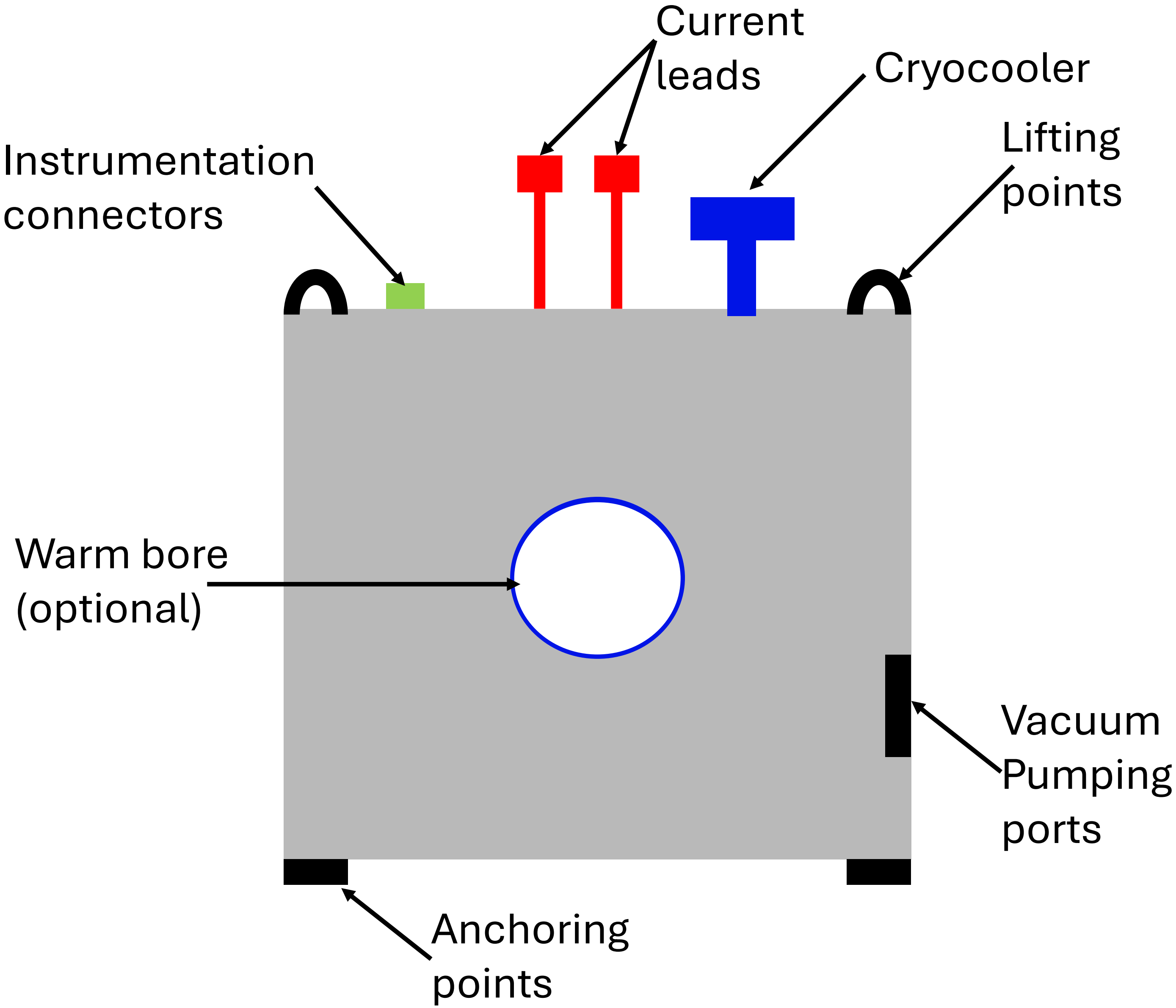
PSI CPT
D. Meer
T. Lomax

AC losses test facility

🟦 Potential external cooperation (EU institutes, companies at Park Innovaare,...)
🟩 Potential cooperations with PSI groups

Three work packages : DC and AC superconducting magnets
Advanced cryogenics (Pulsating Heat Pipes)

HTS demonstrator



Current leads

Cryocooler

Lifting points

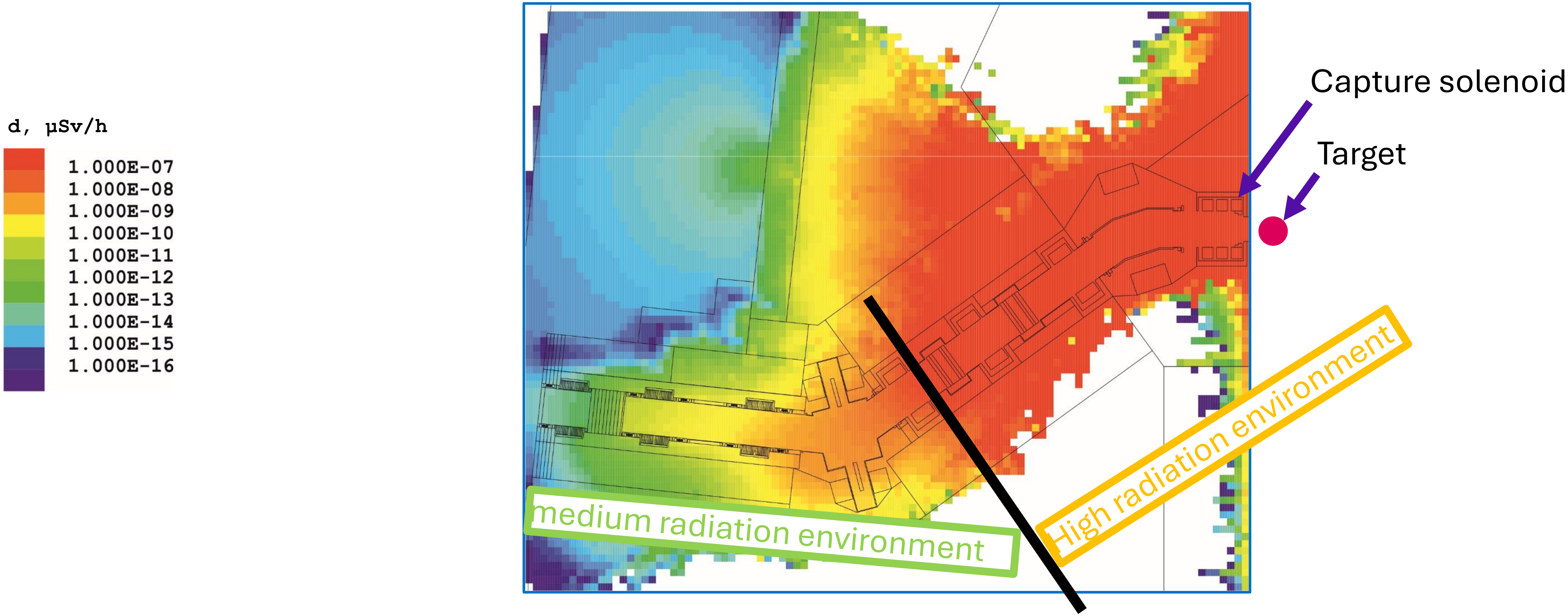
Instrumentation connectors

Warm bore (optional)

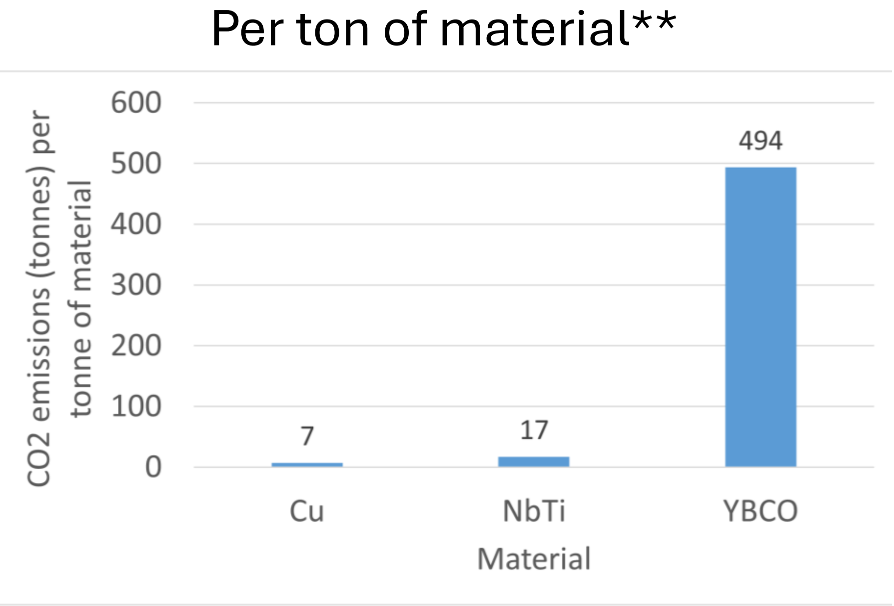
Vacuum Pumping ports

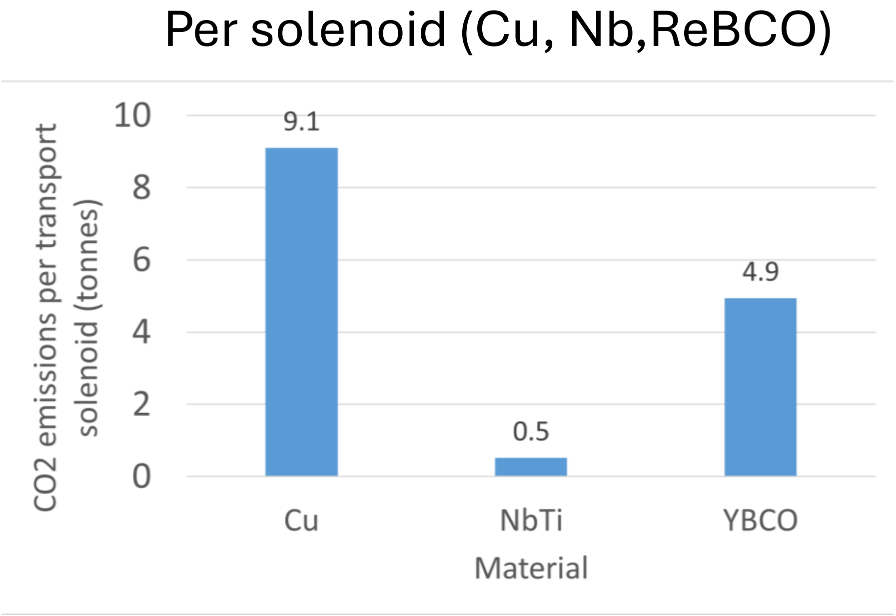
Anchoring points

HiMB: MuH2 beamline – radiation levels



Environmental Impact : CO_2 Emission figures





*Sources: Hartikainen et al. “A Comparative Life-Cycle Assessment Between NbTi and Copper Magnets”; IEEE Transactions on Applied Superconductivity (Volume: 14, Issue: 2, June 2004)

*A. Buchholz, “Prospective Life Cycle Assessment of High-Temperature Superconductors for Future Grid Applications”. Thesis , KIT (2022)